Extreme ultraviolet interferometry: at-wavelength testing of optics for lithography

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INTRODUCTION

Extreme ultraviolet (EUV) lithography is a promising and viable candidate for circuit fabrication with 0.1-micron critical dimension and smaller. Recently voted by a group of semiconductor industry leaders as the most viable next-generation lithography candidate, EUV lithography research is conducted by a large-scale collaborative effort involving three national laboratories (Lawrence Berkeley, Lawrence Livermore, and Sandia National Laboratories, collectively called the *Virtual National Laboratory, or VNL*) and the industry-sponsored EUV Limited Liability Corporation (EUV LLC), which includes Intel, Motorola, and Advanced Micro Devices. A number of other groups around the world are also involved in EUV lithography research, including both Japanese and European efforts.

Operating near 13-nm wavelength, optical systems for EUV lithography require multilayer-coated, all-reflective elements with a system numerical aperture of 0.1 or higher. In a region of the spectrum where all materials are highly absorptive, the mirrors utilize molybdenum/silicon multilayer coatings to achieve reflectivities near 70% at normal incidence. The suggested wavefront aberration tolerance for these sophisticated systems, composed of aspherical elements, is only 0.27 nm, or one-fiftieth of an EUV wavelength [1]. This places extremely high demands on the fabrication of EUV mirror substrates and multilayer coatings, and even higher demands on the metrology tools required to characterize them.

The EUV wavefront is determined by a combination of the geometric figure of the mirror surfaces and the properties of the multilayer coatings, which are deposited across mirror areas of several square inches. While advanced visible-light interferometric techniques possessing the required measurement accuracy are being developed [2], phase effects arising from multilayer coating defects and thickness errors are measurable only at the EUV operational wavelength. Final alignment and qualification may require *at-wavelength*, using EUV light, to successfully predict the imaging performance of an optical system. These factors motivate the development of high-accuracy EUV wavefront-measuring interferometry now in progress at the ALS.

A NOVEL EUV INTERFEROMETER DEVELOPED FOR HIGH-ACCURACY

Researchers from LBNL's Center for X-Ray Optics have built a prototype EUV phase-shifting point-diffraction interferometer (PS/PDI) [3, 4, 5] at ALS beamline 12.0.1.2. By spatially-filtering undulator radiation, the interferometer takes advantage of the high brightness from the ALS to generate coherent EUV light.

The PS/PDI is a common-path interferometer that incorporates pinhole diffraction to generate reference wavefronts of extraordinarily high spherical accuracy. A schematic of the optical design of the PS/PDI is shown in Fig. 1. Open-stencil pinholes smaller than 100-nm diameter are used to test the latest high-quality EUV optics. A coarse grating beam splitter placed before the test optic divides the beam into multiple diffractive orders that are brought to spatially separated

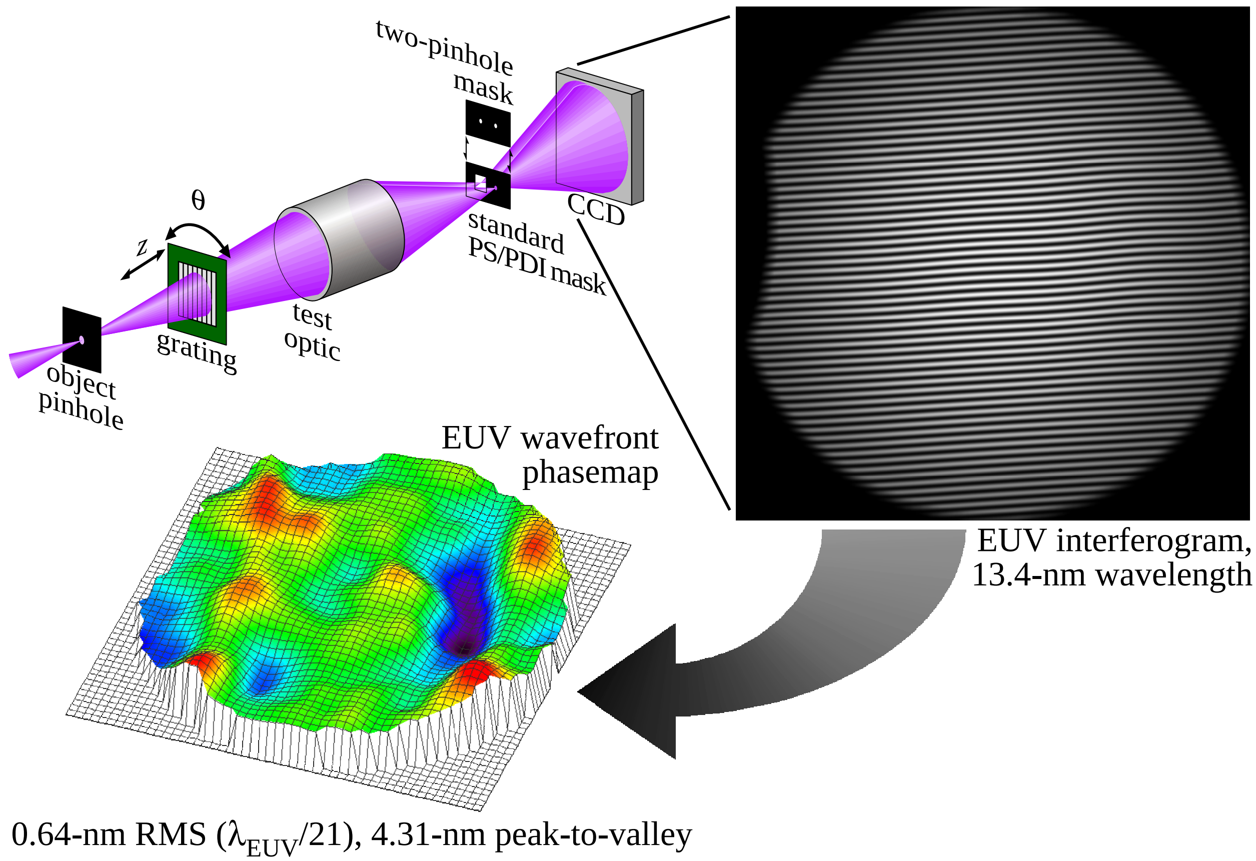

Figure 1. The extreme ultraviolet phase-shifting point diffraction interferometer (EUV PS/PDI) is designed to measure EUV optical systems with sub-angstrom accuracy. Probing the combined surface figure of the multilayer-coated, reflective elements *at-wavelength*, the PS/PDI reveals aberrations on the angstrom scale. Here an interference pattern from the measurement of an off-axis sub-aperture of a 10x Schwarzschild objective shows that nearly diffraction limited performance has been achieved, with RMS wavefront aberrations below one-twentieth of an EUV wavelength in a numerical aperture of 0.088.

foci in the image-plane. One beam, the *test* beam, containing the aberrations of the test optical system, is allowed to pass through a large window in an opaque mask placed in the image-plane. A second beam, the *reference* beam, is spatially filtered by a pinhole smaller than the diffraction-limited resolution of the test optic, and becomes the spherical reference wave. These two beams overlap to produce an interference fringe pattern that is detected by an EUV CCD detector. The interference pattern may be interpreted as a coherent comparison of the aberrated test beam with the nearly-perfect spherical reference beam. The fringe pattern thus reveals the aberrations in the test optic. Translation of the grating beam splitter is used to introduce a controlled relative phase-shift between the test and reference beams, allowing phase-shifting interferometry techniques to be employed.

NEW OPTICS AND NEW MEASUREMENT CAPABILITIES

The focus of the interferometry research in 1998 was on the measurement of new 10× Schwarzschild objectives fabricated to the same tight figure and finish specifications as the coming generation of four-element EUV lithographic optics. Additional research was conducted to calibrate the performance of the interferometer and to advance several new interferometric testing strategies.

Of the two new optics measured in 1998, both systems had wavefront figure errors below 1 nm rms, with one as low as 0.64 nm—better than its design specification. One such wavefront is shown in Fig 1. Favorable comparisons have been made of EUV and visible-light interferometric measurements performed on the same optical systems.

In an effort to characterize and extend the accuracy of the interferometer, a two-pinhole *null test* interferometer calibration was developed. Such a test filters the aberrations from the test optic using a pair of tiny pinholes, and produces the interference of two nearly-perfect spherical reference waves in a configuration similar to Young's famous experiment. Measurement of the residual aberrations allows the accuracy of the interferometer to be probed and geometric effects to be identified. Previous null-test experiments had verified the accuracy of the interferometer from 100-nm diameter pinholes as 0.5 Å rms ($\lambda/250$ at 13.4-nm wavelength). Continued experiments have since pushed this level to 0.4 Å rms ($\lambda/330$) using 80-nm diameter pinholes [6]. Since the pinhole functions as a spatial filter for the aberrated test beam, it is expected that as higher quality-optics are tested, the reference wavefront quality can be further improved.

As smaller pinholes are used to improve the measurement accuracy, the strength of the reference beam decreases and the fringe contrast suffers. This year, new strategies were implemented to improve the interferometer's fringe contrast from below 10 percent to over 80 percent. Fringe contrast has a significant impact on both measurement precision, and the ease with which the interferometer can be aligned. Combined with the increased fringe contrast, new features in the window/pinhole masks and new real-time analysis methods have reduced the time required for alignment of the interferometer from hours to minutes.

Due to the short wavelength of EUV light EUV optics are especially vulnerable to *flare*. Flare is the unwelcome distribution of light around bright image features caused by roughness in the projection optics. Of primary concern is a difficult-to-measure range of mid-spatial-frequency roughness accounting for surface errors of sizes between the large-scale *figure* errors and small-scale *finish* errors. To date, a great effort has been spent to reduce roughness and mitigate the flare problem; part of that effort has been in improved metrology, including at-wavelength scatterometry [7] and other complementary measurement techniques. Recently, the spatial-frequency-response of the PS/PDI has been extended into the mid-spatial-frequency regime, with the ability to measure sub-mm sized features with hundreds of cycles across the aperture. The advances in the PS/PDI's flare measurement capabilities have been made possible by a recently-developed noise-suppressing analysis method and improved window/pinhole mask designs.

REMARKS FOR FUTURE WORK

In 1999, a new PS/PDI is being built on a branchline of beamline 12.0.1. The new interferometer is designed to measure a large-field, four-mirror EUV lithographic optical system with 0.1 NA. This so-called *projection-optics box* (POB) [8], represents the combined efforts of the Virtual National Laboratory and presents the interferometry team with its first opportunity to measure and align an EUV optical system suitable for commercial applications. The POB has a four-mirror ring-field design, and contains aspherical optical elements. Continued interferometry research efforts will explore the extension of the PS/PDI to higher numerical apertures, and different configurations, and will include further collaborations with our VNL partners in the development and testing of EUV optics.

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